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Life cycle assessment of wood-based heating in Norway

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Abstract
Background, aim, and scope In this study, we evaluate the environmental effects of wood-based household heating. Wood is a significant source of household heating in Norway, and a comparative life cycle assessment of a wood-based heating system using an old and a modern stove was conducted to estimate the total life cycle benefits associated with the change from old to new combustion technology.
Materials and methods The study uses a new approach to complete the inventory. Input–output data are used in combination with the Leontief price model to estimate inputs of products and services from the background economy to the birch wood supply chain.
Results When comparing new and old stove technology, the results show that the new technology contributes to a significantly improved performance (28–80%) for all types of environmental impact studied. As there is a large share of old wood stoves still in use, replacing the old stoves with new ones can lead to substantial reductions in environmental impacts, especially impacts affecting human health. The use phase, i.e., wood combustion, is responsible for over 60% of the impact within all categories. Both the old and new stove provide heating with emissions of greenhouse gases ranging from one third (new stove, ~80 g CO_2-eq/kWh) to half (old stove, ~110 g CO_2-eq/kWh) of the impacts compared to electricity use from the Nordic electricity mix (~210 g CO_2-eq/kWh) to heat the house.
Discussion Combustion of the wood is found to be most important for all types of impacts, even for global warming, where the CO_2 emissions from combustion are treated as "climate neutral." Products of incomplete combustion are the reason for this, as well as the high contribution to other impact categories. Emission factors for these substances are subject to high uncertainty. Although the combustion phase is the most important stage in the life cycle, transportation distances can play an important role. To render wood as environmentally benign as possible, one should thus seek to shorten the distances from producer to consumer.
Conclusions There is a significant difference in the life cycle performance of a wood stove using modern technology versus older technologies within all impact categories. In addition, there is a preference to use locally produced firewood over wood transported over long distances.
Recommendations and perspectives A strong emphasis on phasing out old woodstoves should be maintained and is well justified.

Keywords Birch wood · Household heating · LCA · Norway · Wood-based household heating · Wood stove

1 Introduction

In this paper, a life cycle assessment (LCA) of residential wood-based heating is presented. The LCA includes the production and use of firewood in two types of wood stoves. Life cycle assessment is a method that systematically accounts for pollution and resource use connected to delivering a specific product or service. LCA identifies environmental hot spots and enables comparison with other

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energy sources for residential heating. Two types of stove technology were evaluated, a modern clean-burning stove and a traditional stove design. We quantify the emissions and resource use of these technologies using a hybrid LCA approach (Strømman and Solli 2008) and evaluate their environmental impact within a number of categories using characterization factors from the Institute of Environmental Sciences in Leiden (2004) and Hertwich et al. (2006).

The promotion of biomass is an important element in policies aimed at reducing CO_2 emissions from energy production, assuming biomass combustion has zero net global warming potential[1]. On the other hand, wood combustion is one of the largest contributors to local air emissions. In 2000, 64% of all particulate matter emissions in Norway were generated by residential wood combustion. Apart from particulate matter, wood combustion is also a significant emission source of compounds that may be harmful to health, such as polycyclic aromatic hydrocarbons (PAHs), non-methane volatile organic compounds (NMVOCs), dioxins, and CO (Haakonsen and Kvingedal 2001).

There are, however, large differences in emissions and efficiency depending on the stove design and how the stove is used. New, clean-burning stoves emit significantly lower amounts of local air pollutants than traditional stoves. Emissions stemming from incomplete combustion are strongly related to the mode of burning (Karlsvik 2005, personal communication), such as how often new wood is fed into the stove, and how much air is available for combustion. While firing habits were continuous in the past, they have become more discontinuous, requiring improved control of the combustion process and air flow. New stoves can deliver this.

Of all firewood in Norway, 67% is burnt in traditional stoves, 4% in open fire places, and 29% in new “clean-burning” wood stoves[2] (Statistics Norway 2005). There is thus significant potential for improvement with respect to local air pollution and energy efficiency in residential wood combustion.

Several studies aiming at evaluating the environmental performance of wood production for materials or energy purposes have been carried out (Michelsen et al. 2008; Herendeen and Brown 1987; Petersen and Solberg 2004; Athanassiadis 2000; Nussbaumer and Oser 2004; Berg and Lindholm 2005; Werner et al. 2007; Petersen and Solberg 2005; Seppälä et al. 1998; Forsberg 2000). Although not directly aimed at evaluating household heating, they provide insights to the wood production fuel chain. In addition, several studies measuring emissions from wood combustion have been performed (Hedberg et al. 2002; McDonald et al. 2000; Finstad et al. 2003; Haakonsen and Kvingedal 2001; Johansson et al. 2004). Herendeen and Brown (1987), Lenzen (2002), and Holmijoki and Paloviita (2001) apply an input–output-based LCA approach for the inventory compilation in a wood system. This study applies a hybrid LCA method to evaluate wood-based heating. The reason for this approach is to capture direct emissions from the basic activities of the fuel chain, in addition to indirect emissions occurring in the background economy.

The Norwegian energy system differs significantly from that of other European countries, especially in the use of electricity for heating buildings. An average Norwegian household consumes 17,400 kWh of electricity per year (Larsen and Nesbakken 2005). Overall, approximately half of the stationary energy consumption in Norway is related to space heating (Norges offentlige utredninger 2004). Electricity is the main energy source for heating in households and covers 80% of energy demand, whereas wood-based heating accounts for approximately 15% (Norges offentlige utredninger 2004). The annual electricity consumption and production balance roughly at 120 TWh (Statistics Norway 2007), but both production and consumption are variable due to variations in climate. Today, hydropower constitutes nearly all the electricity produced, but the steady increase in commercial electricity consumption requires increased imports from neighboring countries, new production capacity, or a shift towards other technologies. One of the strategies of the Norwegian government is to reduce the use of electricity for heating buildings (Olje- og energidepartementet 1999). At present, wood combustion is the most common alternative to electricity for household heating purposes, as approximately two thirds of Norwegian households have a fireplace (Statistics Norway 2004a).

There is, hence, a large potential for increasing the use of wood for heating purposes.

2 Methodology

LCA is used to analyze the environmental impacts throughout the whole life cycle of a product or service, from resource extraction to final disposal. LCA allows the systematic comparison of different processes within a life cycle and of alternative system configurations. In such a

[1] In this study, we assume wood from well-managed forestry to be CO_2 neutral; the annual outtake in Norway is currently well below the annual regrowth (Statistics Norway 2006). This is not uncontroversial as, for example, land use changes according to Reijnders and Huijbregts (2003) and other factors may influence the carbon neutrality of wood. The information on this, however, is limited, and therefore not considered aside from a qualitative mention. For a thorough review on the issue, consult Reijnders (2006). Emissions other than CO_2 from biomass combustion that contribute to global warming, such as methane, of course have to be included.

[2] As of 1998, wood stoves must be classified as “clean burning” to enter the market. This means, in compliance with Norwegian Standard NS 3059 (Norsk Standard 1994).

process, it is important to avoid solving one environmental problem by merely shifting it out of the system analyzed. It is also important to recognize tradeoffs, such as between greenhouse gas emissions and particulate matter.

This study applies a method combining the strengths of LCA (Guinee 2002) with input–output analysis (Leontief 1936) in a hybrid version of LCA (Suh et al. 2004; Treloar 1997; Bullard et al. 1975).

The approach applied here follows the lines of the integrated hybrid approach described by Suh (2004) and Suh and Huppes (2005), where a foreground system described in more detail requires inputs from the background economy, and vice versa, to fulfill a given final demand, in this case, heat from a wood stove. The approach used here has been developed by Strømman and Solli (2008). It enables the completion of inventories from input–output data, utilizing knowledge of product prices. The method ensures 0% cutoff with respect to costs. Principally, input–output-based data are combined with original key data and adapted to represent the input structure of the processes in question. The application of Leontief's (1936) price model is essential in doing this. The method of Strømman and Solli (2008) requires an identification of which sectors of the economy the various foreground processes belong to. The input structure of these sectors is used as models for the missing inputs. Further, the structures are scaled so that they, together with the original key data, satisfy the Leontief price model. The resulting hybrid LCA structure is then a model that is valid in both the primal and dual form. That is, it has a consistent representation of both the flow of inputs and outputs and the cost structure.

An LCA can be expressed in a single equation. The result is a vector d of environmental impact potentials:

$$d = CF(I - A)^{-1}y \tag{1}$$

where matrix F contains the emissions factors and resource use factors per unit of process or economic activity and C contains characterization factors that relate the different emissions to different types of environmental impact. $(I{-}A)^{-1}$ is termed the Leontief inverse; this matrix contains the total output of individual processes per unit final demand of any process in the system. y is the vector of final demand.

The requirements and emission matrices for the system are constructed as follows:

$$A_{ij} = \begin{bmatrix} A_{ff} & 0 \\ A_{nf} & A_{nn} \end{bmatrix} \qquad F_{ij} = \begin{bmatrix} F_f & F_n \end{bmatrix} \tag{2}$$

Any column a_i in A contains the "cookbook recipe" of inputs required to produce one unit of output from process i. A_{ff} is the foreground process interrequirement matrix; A_{nn} is the background economy interrequirement coefficients matrix and A_{nf} represents the inputs of commodities to the foreground system. For the purpose of this study, the demand of processes included in the foreground system from the background economy is assumed to be zero. This means that the upper right quadrant in the matrix is set to zero[3]. In the same way, a column f_i in F displays the emissions connected to producing one unit from this process. F_f includes the emission intensities of the foreground processes and F_n the emission intensities of the background commodities.

We use characterization factors from the Institute of Environmental Sciences (2004) in Leiden for all impacts except human toxicity, where we use factors from Hertwich et al. (2006). We constructed human toxicity potential (HTP) factors for NMVOC emissions by assuming the same mixture of substances as in Johansson et al. (2004). Substances not included in Hertwich et al. (2006) were assumed to have zero impact.

3 System description

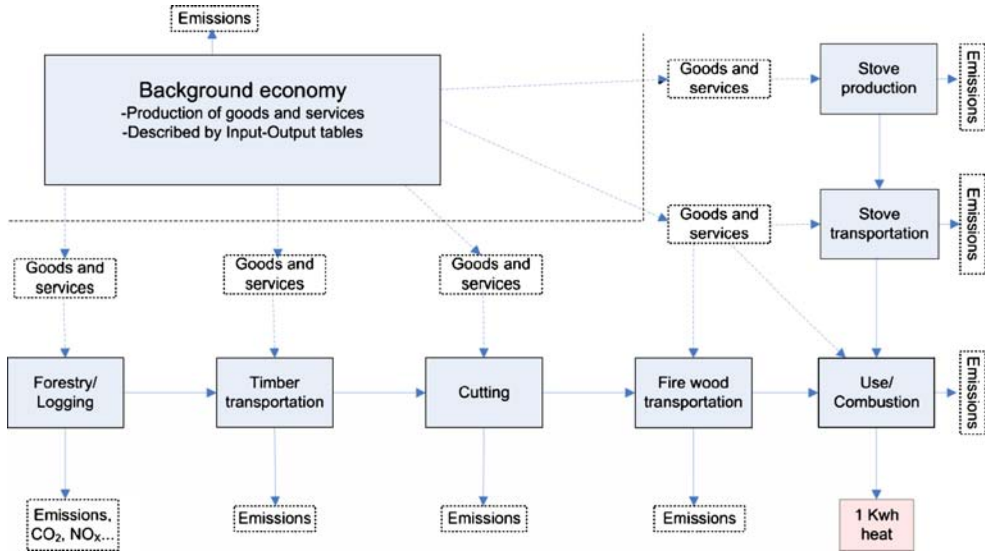
The function of the studied system is to provide space heating for households. The functional unit has been set to 1 kWh of heat delivered in a household. An overview of the system is given in Fig. 1. The figure shows the firewood production from forestry to combustion and the stove from production to use. The dotted line illustrates the border between the foreground and background system. The arrows into the system represent in-going goods and services whereas the arrows out of the system represent emissions.

For this study, birch was chosen as firewood. Birch has a lower heating value (LHV) of about 2,650 kWh per solid cubic meter (sm^3) and is one of the most common types of firewood in Norway. The value chain for the production of birch firewood can be divided into four main phases: forestry and logging, transportation to the production facility, cutting, and transportation to the consumer or local dealer. Data on resource use in the operations were collected from various sources (Avdem 2005, personal communication; Raaen 2005, personal communication; Lileng and Kjølset 2005, Skogforsk note sent by e-mail) as were the costs (Lileng and Kjølset 2005, Skogforsk note sent by e-mail) along the value chain.

Birch regrowth in Norway generally occurs by natural growth. Nevertheless, some planting activity does take place in southern Norway, but the activity is insignificant when compared to natural regeneration (Avdem 2005, personal communication). For this reason, there is little resource use for birch wood production before logging.

[3] For a discussion on the validity of this assumption, see Peters (2006) and Suh (2006).

Fig. 1 System flowchart



The logging process is usually performed on frozen ground, i.e., from November to April. The use of modern technology such as logging machines and terrain transportation vehicles constitutes nearly all logging activities for birch fuelwood production (Statistics Norway 2004b). However, the resource use in the felling process strongly depends on the terrain. Steep terrain is less efficient to log, resulting in increased fuel use. The emission data in this study are based on typical average Norwegian conditions for logging of birch. It is assumed that the felling and transportation process is performed using modern cutting machines, transportation machines, and trucks. The fuel use and, hence, the direct emissions for the logging process are provided by Raaen (2005, personal communication). The costs of felling and terrain transport will vary with wood type, terrain conditions, transportation distance, and the resource cost that goes to the owner of the forest. The costs used in the hybrid inventory (Lileng and Kjølset 2005, Skogforsk note sent by e-mail) are average values for Norwegian conditions.

Timber is usually transported by log trucks to the production site, where it is cut into pieces suitable for utilization in stoves. The costs and fuel use for truck transportation are provided by Lileng and Kjølset (2005, Skogforsk note sent by e-mail), assuming a transport distance of 50 km and a truck weight of 50 tonnes. The truck has a capacity of 30 sm^3 of timber. There will be large differences in transport distances depending on the wood producer (Lileng and Kjølset 2005, personal communication).

The timber is cut with a circular saw with either manual or automatic feeding, put into sacks, and stored to dry at a fuelwood production site. Normally, the cutting takes place in winter/spring and then storage in summer. The dried wood is subsequently sold during the autumn (Avdem 2005, personal communication). The maximum allowed moisture content in fuelwood is set to 20% (Norsk Standard 1997). An estimated loss, i.e., cuttings and sawdust, of 10% occurs in the cutting process (Espegaard 2006, personal communication, www.norskved.no).

The transportation mode from the production site to the consumer varies widely. The wood may be picked up at the production site by the consumer or delivered by the manufacturer. In some cases, a distributor picks up the fuelwood or gets it delivered by the manufacturer for resale. Most of the fuelwood in Norway, however, is delivered directly to the consumer by the manufacturer (Lileng and Kjølset 2005, Skogforsk note sent by e-mail); this scenario is also the basis for this study. An average transportation distance of 180 km and wood delivered in sacks of 1.5 m^3 are assumed. The firewood is further assumed to be transported with a 10-tonne truck, loaded at 50% capacity at all times. The truck has a capacity of 20 sm^3 of fuelwood (Avdem 2005, personal communication).

Direct emissions from transportation processes have been calculated using emission factors from Spielmann et al. (2007).

In this assessment, we illustrate the stove with a model similar to Jøtul F602. This is a very popular model, both in size and type (Jøtul 2005). Note that emission data are not specific to this stove; we assume that the approximate same stove exists in both clean-burning and old versions. The construction of the stove is completely modeled as a purchase from the background economy. The cost of the stove, both with new and old technology, is estimated at approximately 5,000 NOK including tax. The transportation distance between the production facility and the consumer via a supplier and a store is assumed to be 300 km. The installation is assumed to be carried out by the house owner and is not included in the study. The end of life of the stove is not included.

The combustion rate is assumed to be 1–1.25 kg/h during operation, based on estimates of average burning habits (Haakonsen and Kvingedal 2001). The emissions from residential wood combustion vary with a number of factors such as the stove design and technology, the combustion rate (kg wood per hour) and the numbers of hours of operation, fuel properties (type of wood, humidity, chemical composition), and the maintenance of the stove (Karlsvik 2005, personal communication).

Recommended emission quantities for calculations per kilogram of wood burned under Norwegian conditions are given by Statistics Norway (SSB). These values can be seen in Table 1. The emission data concern quantities for unspecified firewood, but, due to the mentioned uncertainties and the nonnegligible fact that the emission values are valid for Norwegian burning habits, they were deemed satisfactory for burning of birch wood in this analysis.

The average *efficiency* of wood stoves (wood LHV to useful heat delivered in household) is hard to estimate, as it depends on a number of factors that are essentially unknown. These factors include the maintenance of the stove, the length of the connection pipe to the chimney, ventilation effects, etc. and all factors have a potentially large impact on the overall efficiency of the wood stove. Moreover, burning habits complicate the picture. The expected efficiency is generally lower than what is achieved in laboratory tests, and an overall efficiency of 70% for a modern stove and 50% for a traditional stove is thus assumed. This is in line with ranges given by the US Environmental Protection Agency (2009). The efficiencies are highly uncertain and results will naturally be very sensitive to this parameter. Furthermore, a lifetime heat production of 300,000 kWh is assumed.

Table 1 Emissions from residential wood combustion (Haakonsen and Kvingedal 2001)

Pollutant	Emissions[a] [kg/kg wood combusted]	
	New stove	Old stove
CH_4	5.8E−03	5.8E−03
N_2O	3.2E−05	3.2E−05
SO_2	2.0E−04	2.0E−04
NO_x	9.7E−04	9.7E−04
NMVOC	7.0E−03	6.9E−03
CO	5.1E−02	1.5E−01
$PM_{2.5}$[b]	6.3E−03	4.0E−02
Cadmium	1.0E−07	1.0E−07
PAH-4[c]	2.5E−08	2.7E−06
Dioxin[d]	1.0E−12	1.0E−12

[a] The emissions are calculated by SSB (Haakonsen and Kvingedal 2001) for Norwegian conditions

[b] The emissions are given as PM_{10}, but we assume all the particles to be in the $PM_{2.5}$ category based on Hedberg et al. (2002) and Boman et al. (2005)

[c] LRTAP: Convention on Long-Range Transboundary Air Pollution (Haakonsen and Kvingedal 2001)

[d] Report on dioxin emissions in Norway from Statistics Norway (Finstad et al. 2002)

The most likely waste scenario for the ashes is the municipal waste management or household gardens. This has not been included in the assessment, under the assumption of negligible environmental impact compared to the rest of the system.

A modified version of the official Norwegian IO table for 2000 (Statistics Norway 2001) was used for the analysis together with data on sectorial emissions (Statistics Norway 2008)[4]. We use basic prices in the analysis. We assume the collected prices to be representative of year 2000, although the information on price-year is limited and may vary. The uncertainty introduced by this assumption is limited compared to other uncertainties associated with the type of approach used.

Statistics Norway only publishes emission figures for the pollutants listed in the supplemental information; these are hence the only emissions considered in the assessment, although more comprehensive data are available for certain parts of the system.

The interprocess demand in the foreground system is presented in the A_{ff} matrix. The F and A_{nf} matrix were constructed from the collected emission data and economic data as well as A_{nn}, using the approach described by Strømman and Solli (2008). The inventory data are available in the "Supplemental information."

4 Results and discussion

The life cycle inventory results of the two cases are presented in Table 2. We notice that the reduction in emissions varies from about 25%—an effect purely caused by higher efficiency and reduced demand of upstream processes—to 99%—a result of significantly improved combustion conditions.

The life cycle impact assessment results shown in Table 3 indicate the importance of the type of technology on an impact level. The old stove technology was chosen as a reference case and we indicate the improvement in each impact category relative to this case. The stove technology is important for all selected impact categories but particularly for toxic impacts.

[4] The modified version contains the data for tobacco production and petroleum refining in separate sectors; these are aggregated into other sectors in the public version due to confidentiality issues.

Table 2 Life cycle inventory for 1-kWh heat delivered in household

Substance	Unit	Old stove	New stove	Change
CO_2	kg	3.6E−02	2.6E−02	−28%
CH_4	kg	2.9E−03	2.1E−03	−29%
N_2O	kg	1.9E−05	1.3E−05	−28%
SO_2	kg	1.1E−04	8.0E−05	−28%
NO_x	kg	7.7E−04	5.5E−04	−28%
NMVOC	kg	3.5E−03	2.5E−03	−29%
CO	kg	7.3E−02	1.8E−02	−76%
NH_3	kg	1.5E−06	1.1E−06	−27%
PM_{10}	kg	8.5E−06	6.3E−06	−27%
$PM_{2.5}$	kg	1.9E−02	2.2E−03	−89%
Lead	kg	2.3E−09	1.7E−09	−26%
Cadmium	kg	4.9E−08	3.5E−08	−29%
Mercury	kg	2.4E−10	1.8E−10	−25%
Arsenic	kg	6.4E−10	4.8E−10	−25%
Chrome	kg	3.9E−09	2.9E−09	−25%
Copper	kg	1.5E−08	1.1E−08	−28%
PAH-4	kg	1.3E−06	1.0E−08	−99%
Dioxins	kg	4.9E−13	3.5E−13	−29%
Cost (excl. VAT)	NOK	7.0E−01	5.0E−01	−28%

The analysis shows that, even if we consider biomass emissions of CO_2 "neutral," there are emissions of greenhouse gases associated with its production and use. Even so, a global warming potential of about 110 g CO_2-eq/kWh for an old stove and about 80 g CO_2-eq/kWh for a new stove indicates a reduction compared to 1-kWh heat delivered by electricity from the Nordic mix NORDEL of 210 g CO_2-eq/kWh (Dones et al. 2007). We assume that this mix represents the marginal electricity in Norway. Other types of impact are harder to compare to the work of Dones et al. (2007) since the types of emissions included for these impacts are different.

The contribution of different processes and pollutants to the category indicator results is presented in Tables 4 and 5. The results clearly indicate that the use phase, that is the combustion of the wood, is the dominant source of pollution for all impact categories. Products of incomplete combustion, such as methane, dioxin, NMVOCs, PAHs, and particulates (as $PM_{2.5}$) are the dominant contributors to most impact categories. As we have indicated earlier, there are significant uncertainties and variabilities connected to the emissions rates of these pollutants. Our results are therefore sensitive to the emissions' measurements for the wood stoves and the extrapolation of these into real-life usage.

It should be noted that the improved combustion process ensures substantially reduced emissions of PAHs, $PM_{2.5}$, and reduced emissions of NMVOCs, and this is reflected in the human toxicity and photochemical oxidation categories.

We assume the same emission rates of dioxin and methane per kilogram wood for both stoves, so differences in the emissions of these pollutants reflect the reduced amount of wood combusted for the more efficient stove.

Surprisingly, dioxin is the most important pollutant for noncancer human toxicity categories in a new stove and has a higher contribution than the much-debated particles. For an old stove with higher particle emissions, $PM_{2.5}$ still contributes most to the noncancer toxicity.

The reduction in $PM_{2.5}$ emissions from the combustion phase alone reduces the noncancer HTP for the new stove by 47% compared to the old type. The remainder of reductions is due to lower emissions of other substances and reduced demand of upstream processes. The cancer HTP is mostly reduced due to lower emissions of PAH from combustion. This accounts for as much as 70% points of the total reduction (80% points) in cancer HTP.

It should be emphasized that these results are quite uncertain. There are several factors that could potentially affect these conclusions.

First, the emissions factor for dioxin of 1-ng/kg wood (Finstad et al. 2002) was not directly measured in the experiments on Norwegian stoves but taken from the literature based on tests outside of Norway. In a comprehensive review of emissions from wood boilers, Lavric et al. (2004) reported emission factors of 0.2–5.1 ng/kg for uncontaminated wood. In a series of field measurements of domestic heating appliances, Hubner et al. (2005) measured levels corresponding to 0.4–81 ng/kg for wood stoves and somewhat lower numbers for boilers. These recent measurements tend to be higher than the ones that were the basis for the emission factors used by Statistics Norway (Finstad et al. 2002).

Second, there is substantial uncertainty also connected to the particulate matter emissions. Measurements in Sweden, however, indicate that the emission factor for new stoves is used here on the high side (Johansson et al. 2004; Hedberg et al. 2002).

Finally, the characterization factors for the human toxic impact consider both the toxicity of the chemicals as

Table 3 Results for delivering 1 kWh of heat from a wood stove using old and new stove technology

Impact category	Unit	Old stove	New stove	Diff.
Global warming	kg CO_2-eq.	1.1E−01	7.7E−02	−28%
Photochemical oxidation	kg C_2H_2-eq.	5.5E−03	3.0E−03	−45%
Acidification	kg SO_2-eq.	5.2E−04	3.7E−04	−28%
Eutrophication	kg PO_4-eq.	1.0E−04	7.2E−05	−28%
HTP air, cancer	kg benzene eq.	3.8E−03	7.5E−04	−80%
HTP air, noncancer	kg toluene eq.	1.2E+00	4.6E−01	−61%
Cost (excl. VAT)	NOK	7.0E−01	5.0E−01	−28%

Table 4 The five most contributing processes to each impact category for a new clean-burning stove and an old stove

	New stove		Old stove	
	Absolute	Relative	Absolute	Relative
GWP [CO_2-eq.]				
Use	5.0E−02	64.4%	6.9E−02	64.6%
Firewood transport	1.2E−02	15.5%	1.7E−02	15.5%
Logging	4.4E−03	5.8%	6.2E−03	5.8%
Timber transport	2.4E−03	3.1%	3.3E−03	3.1%
Petroleum refining	1.9E−03	2.4%	2.6E−03	2.4%
Photochemical oxidation [C_2H_2-eq.]				
Use	2.9E−03	97.5%	5.4E−03	98.1%
Extraction of oil and gas	2.2E−05	0.7%	3.0E−05	0.5%
Firewood transport	1.7E−05	0.6%	2.4E−05	0.4%
Petroleum refining	1.0E−05	0.3%	1.5E−05	0.3%
Logging	6.5E−06	0.2%	9.1E−06	0.2%
Acidification [SO_2-eq.]				
Use	2.5E−04	67.6%	3.5E−04	67.8%
Firewood transport	6.0E−05	16.0%	8.3E−05	16.0%
Logging	2.2E−05	5.9%	3.1E−05	6.0%
Timber transport	1.2E−05	3.2%	1.7E−05	3.2%
Petroleum refining	3.6E−06	1.0%	5.0E−06	1.0%
Eutrophication [kg PO_4-eq.]				
Use	4.4E−05	61.0%	6.1E−05	61.1%
firewood transport	1.5E−05	20.6%	2.1E−05	20.6%
Logging	5.5E−06	7.7%	7.7E−06	7.7%
Timber transport	2.9E−06	4.1%	4.1E−06	4.1%
Extraction of oil and gas	7.6E−07	1.1%	1.1E−06	1.1%
HTP air, cancer [kg benzene eq.]				
Use	7.3E−04	97.6%	3.8E−03	99.4%
Manufacture of basic nonferrous metals	2.8E−06	0.4%	Less than 0.1%	
Extraction of oil and gas	2.8E−06	0.4%	3.9E−06	0.1%
Firewood transport	2.1E−06	0.3%	Less than 0.1%	
Manufacture of basic iron and steel	2.0E−06	0.3%	Less than 0.1%	
HTP air, noncancer [kg toluene eq.]				
Use	4.5E−01	97.9%	1.2E+00	98.9%
Manufacture of basic iron and steel	2.2E−03	0.5%	2.7E−03	0.2%
Firewood transport	1.5E−03	0.3%	2.1E−03	0.2%
Manufacture of wood and of products of wood	9.9E−04	0.2%	1.4E−03	0.1%
Manufacture of pulp, paper and paper products	7.4E−04	0.2%	Less than 0.1%	
Value added [NOK]				
Cutting	1.7E−01	33.3%	2.3E−01	33.6%
Logging	1.3E−01	25.0%	1.8E−01	25.2%
Firewood transport	5.8E−02	11.5%	8.1E−02	11.6%
Extraction of oil and gas	2.5E−02	4.9%	3.4E−02	4.9%
Wholesale and retail trade	2.0E−02	3.9%	2.7E−02	3.9%
Timber transport	1.6E−02	3.1%	2.2E−02	3.2%

Table 5 The most contributing substances to each impact category

	New stove		Old stove	
	Absolute	Relative	Absolute	Relative
GWP [CO_2-eq.]				
CH_4	4.7E−02	61.4%	6.6E−02	61.6%
CO_2	2.6E−02	33.4%	3.6E−02	33.3%
N_2O	4.0E−03	5.2%	5.6E−03	5.2%
Photochemical oxidation [C_2H_2-eq.]				
NMVOC	2.5E−03	83.1%	3.5E−03	63.4%
CO	4.8E−04	15.8%	2.0E−03	35.8%
NO_x	1.5E−05	0.5%	2.1E−05	0.4%
CH_4	1.2E−05	0.4%	1.7E−05	0.3%
SO_2	3.8E−06	0.1%	Less than 0.1%	
Acidification [SO_2-eq.]				
NO_x	2.7E−04	73.7%	3.8E−04	73.8%
SO_2	9.6E−05	25.8%	1.3E−04	25.8%
NH_3	1.7E−06	0.5%	2.3E−06	0.5%
Eutrophication [kg PO_4–eq.]				
NO_x	7.1E−05	99.5%	1.0E−04	99.5%
NH_3	3.8E−07	0.5%	5.1E−07	0.5%
HTP air, cancer [kg benzene eq.]				
Dioxins	4.3E−04	57.7%	6.1E−04	16.0%
NMVOC	2.9E−04	39.1%	4.1E−04	10.8%
PAH-4	2.1E−05	2.9%	2.8E−03	73.1%
Arsenic	1.1E−06	0.1%	Less than 0.1%	
Cadmium	9.8E−07	0.1%	Less than 0.1%	
HTP air, noncancer [kg toluene eq.]				
Dioxins	3.1E−01	67.2%	4.4E−01	36.2%
$PM_{2.5}$	7.2E−02	15.6%	6.4E−01	53.4%
Cadmium	6.6E−02	14.3%	9.3E−02	7.7%
CO	4.8E−03	1.0%	2.0E−02	1.6%
Mercury	2.5E−03	0.5%	3.3E−03	0.3%
NMVOC	2.4E−03	0.5%	3.3E−03	0.3%
NO_x	2.4E−03	0.5%	3.3E−03	0.3%
Lead	9.8E−04	0.2%	1.3E−03	0.1%
SO_2	4.8E−04	0.1%	Less than 0.1%	

determined by, in this case, epidemiological studies and the environmental fate of the pollutants. For dioxin, it should be emphasized that the emission factors are for all measured dioxins and furans, aggregated in terms of their relative strength of binding to a receptor, which is taken as an indication of their toxicity. For a discussion of these toxic equivalents, see Hedman et al. (2006). The HTP value used is for 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) and assesses the toxicity *and* exposure of emissions of that chemical. Differences in the exposure of other dioxins and furans are not taken into account. The dominant exposure route for TCDD is through uptake of fatty food, such as milk, meat, and fish (Hertwich et al. 2001). HTP calculations assume that a region is self-sufficient in terms of food, which is clearly not the case for Norway. The exposure fraction of particulate matter depends to a large degree on the residence time in air, as inhalation is the only exposure route assessed. The residence time is higher for smaller particles. A majority of the particles from wood combustion are smaller than 1.3 μm (Hedberg et al. 2002) and are emitted rather close to where humans spend their time, so that the HTP characterization factor of particulate matter probably is an underestimate of the real impact.

Overall, we can conclude that there is reason to be concerned about both dioxin and particulate matter and that there is significant uncertainty about emission rates, as well as the characterization of these emissions. There are substantial reductions in the emissions of PM and PAHs (Table 5) with the new technology, but several authors indicate that the dioxin emissions are not reduced.

The reduced stressor-specific effect of the higher fuel efficiency of the new stove can be seen in several impact categories, and it is both due to the reduction of direct emissions and due to reduced fuel requirements and associated transport. It also leads to a lower life cycle cost compared to the older stove. Although the results are sensitive to the uncertain parameter of stove efficiency, this effect is fairly predictable, as results scale proportional to the indicated efficiencies both in the use phase and in upstream processes. This means that a change in the efficiency by 1% point away from 0.70 to 0.71 (for the new stove) increases all emissions by approximately 1.4%. The emissions from stove construction and transportation remain constant but are almost negligible with respect to this, so it is safe to say that the emission scale is proportional to the efficiency. For the old stove, a 1% point change would result in 2% change in emissions. The uncertainty in efficiency does not affect conclusions as the

Table 6 The most important structural paths contributing to global warming for a stove with new stove technology fueled on local firewood

Contribution	Path
64.4%	Use
15.5%	Use → firewood trsp.
5.8%	Use → firewood trsp. → cutting → timber trsp. → logging
3.1%	Use → firewood trsp. → cutting → timber trsp.
1.3%	Use → firewood trsp. → manuf. of petroleum products
0.7%	Use → firewood trsp. → manuf. of petroleum products → extr. crude petroleum
0.5%	Use → firewood trsp. → cutting → timber trsp. → logging → manuf. petroleum prod.

Table 7 The ten most important structural paths contributing to value added for heat from a clean-burning stove

Contribution	Path
33.3%	Use →firewood trsp. → cutting
25.0%	Use → firewood trsp. → cutting → timber trsp. → logging
11.5%	Use → firewood trsp.
3.1%	Use → firewood trsp. → cutting → timber trsp.
2.3%	Use → firewood trsp. → manuf. petr. prod. → extr. crude petr.
0.9%	Use → firewood trsp. → wholesale/retail; repair of motor vehicles
0.8%	Use → firewood trsp. → cutting → timber trsp. → logging → manuf. petr. prod. → extr. crude petr.
0.8%	Use → stove trsp. → stove transportation
0.8%	Use → firewood trsp. → cutting → electricity
0.5%	Use → firewood trsp. → cutting → manufacture of and products of wood

efficiency ranges given by the US Environmental Protection Agency (2009) do not overlap, and the specific emissions factors per kilogram wood combusted are higher for the old stove technology.

In addition to the stove technology, the distance for the firewood transportation is an important factor. For a new stove, the emissions from transportation of the firewood constitute about 16% of total global warming potential (GWP). If the transportation distance is multiplied by 4 to 5 when importing firewood, transportation would become the most important source of emissions affecting global warming. The overall performance of wood as an energy source depends on the performance of the firewood system as a whole, from producer to consumer. As long as there is a local resource base of wood, short transportation distances should be preferred.

The use phase and, hence, combustion of the wood are the most important processes for all impact categories. This may be a surprise for the GWP, as the CO_2 emissions from wood combustion are counted as “neutral'” in a global warming context. Table 5 shows that methane emissions account for the majority of this contribution to the GWP. Firewood transportation and associated fuel production are also relevant for the GWP. The methane emissions result from incomplete combustion, which in turn depends on temperature, draught, humidity, and, hence, firing habits. The emission factors are calculated from carbon and hydrogen content from wood combustion and must be handled with care (Haakonsen and Kvingedal 2001). Johansson et al. (2004), however, have carried out measurements resulting in amounts and fractions of methane to NMVOCs from wood combustion similar to the values used in this assessment. Table 6 details the most important cause–effect relationships for each contributor to global warming, as determined by structural path analysis (Peters and Hertwich 2006).

With respect to photochemical oxidation, the type of stove technology is much more relevant to the overall results of the system than the wood transportation distance. NMVOCs are the most important substances in this category and a majority of their emission comes from operation of the stove as a result of incomplete combustion. For acidification and eutrophication, however, nitrogen oxide, NO_x, is the most important substance. A majority of the NO_x emission occurs during use

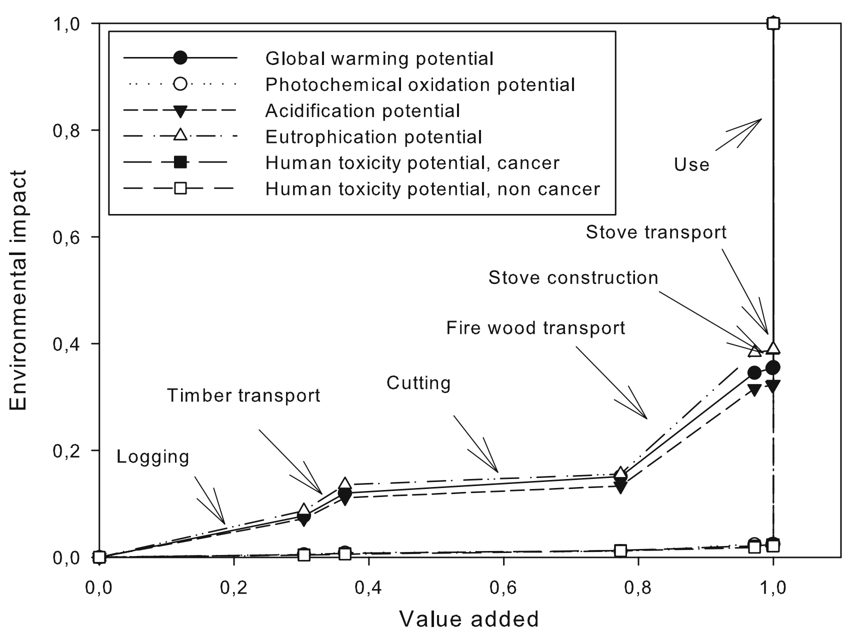


Fig. 2 The relationship between environmental impact and value added for the included processes, clean-burning stove

and wood transportation. Almost all NO_x emissions in the use phase are caused by nitrogen in the fuel itself; thermal NO_x is only a small fraction for solid biofuel combustion (Obernberger et al. 2006), limiting the ability to mitigate these emissions.

The total cost of providing 1 kWh of heat when using local firewood with new or old stove technology is 0.50 and 0.70 NOK (excluding value-added tax), respectively, see Table 3. Cutting and logging are the two most contributing activities, followed by the transportation of firewood and timber. This is not surprising as these activities are quite labor intensive. We can follow the cause–effect chain that leads to value added in these activities by looking at structural paths; see Table 7. Note that the value of a standing forest as a resource is included in the value added of logging.

Figure 2 shows the contribution of the different processes along the value chain to the different impact categories as a function of the value added in the processes. The *y*-axis represents the cumulative environmental impact and the *x*-axis the cumulative value added. The steeper the line is, the higher environmental impact per value added. The vertical curve in the use phase is a result of no value being added during use of the stove.

Generally, the contribution from processes in the foreground system is dominating over activities in the background system. For all impact categories, less than 11% of the impact occurs outside the foreground system. For value added a larger fraction, about 26% occurs in the background, something that can be expected as the use phase adds significant impact but no value added. The high contribution from foreground processes indicates a well-described foreground system.

5 Conclusions

The results from the present life cycle assessment show that the new stove technology significantly improves the performance (28–80%) for all types of environmental impacts studied. As long as the wood is produced locally, the use phase is responsible for the majority of the impacts. Hence, the replacement of old stoves with new stoves significantly improves the environmental performance of wood stoves for heating. As there is a high share of old stoves in Norwegian households, there is thus significant potential for improvement in residential wood combustion.

Although we have considered the emissions of CO_2 from combustion of biomass "climate neutral," there are greenhouse gas emissions associated with the supply of wood, as well as emissions of methane in the combustion phase. Hence, wood-based heating also contributes to climate change. Compared to supplying the heat with electricity from the average Nordic mix, emissions are about one third to half depending on stove technology.

We should add as a caveat that dioxin emissions are not reduced with new stoves. We find that dioxin is an important contributor to the human toxicity categories, except for cancer risk with old technology, where PAH dominates. The emissions of PAH are almost eliminated with a new stove. There has been some focus in the literature on the dioxin emissions, but there is significant uncertainty regarding these emissions for stoves.

As expected, PM emissions are important for noncancer human health, especially in old stoves. In newer stoves, a larger share of impact is caused by dioxin and cadmium.

Given the significant improvement in changing to new stoves, stronger policies encouraging the replacement of old stoves could be introduced. This can include financial incentives as has been done to facilitate the use of heat pumps and pellet stoves (Enova 2008). The current policy of only allowing *sales* of clean-burning stoves makes the transition slower than it could have been, as the operational lifetime of wood stoves is high.

Although the combustion phase is the most important stage in the life cycle, the transportation distance also plays an important role, especially for long distances. Local solutions for the delivering of firewood seem to be crucial for the level of environmental performance of wood as an energy source.

Given that combustion is the most important process, it should be noted that there is a significant variation between wood types and firing habits and that there are substantial uncertainties concerning the measurements. A more exact identification of hydrocarbon compounds, methane, and volatile organic compounds (VOC) would also be useful since methane has such a high influence on global warming potential and the importance of VOC for human cancer toxicity and photochemical oxidation. The issue of dioxin emissions and their health impact clearly requires more focus; this issue has been more or less ignored compared to particle emissions.

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